ICF CONSULTING

MEMORANDUM

To: Ken Sandler

Cc: Henry Ferland

From: Philip Groth, Deanna Lekas, Anne Choate

Date: May 14, 2003

Re: Background Memo for Developing Green Buildings Emission Factors
(EPA Contract No. 68-W7-0069, Task Order 5010)

This background memo describes the methods and results of our analysis to develop life-cycle greenhouse gas (GHG) emission factors for two building materials – clay bricks and concrete recycled as aggregate – and to quantify the GHG benefit of using recycled-content concrete. The document presents a summary of our findings, followed by three material-specific sections that provide details on emission factor development. It should be noted that this study represents a "snapshot" of typical building materials at the time this report was published. Because the opportunities for resource conservation in the construction industry are growing, the materials covered in this report and the assumptions used to quantify emission reductions may be revisited in future years.

To help put these emission factors into perspective, Exhibit 1 presents the emission factors developed in this analysis, as well as those of selected other materials. Note that factors such as aluminum with very high source reduction and recycling values reflect the energy-related emissions from virgin production processes, particularly when compared to the energy emissions from recycled production processes.

Exhibit 1. GHG Emission Factors for Selected Materials and Waste Management Practices (MTCE/Ton)

Material	Net Source Reduction Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Clay Bricks	(0.07)	NA	NA	NA	0.01
Concrete	NA	(0.0013)	NA	NA	0.01
Aluminum	(2.53)	(4.12)	NA	0.02	0.01
Steel	(0.79)	(0.49)	NA	(0.42)	0.01
Glass	(0.14)	(0.08)	NA	0.01	0.01
Dimensional Lumber	(0.55)	(0.67)	NA	(0.22)	(0.10)

Source: U.S. EPA 2002. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.*

In addition to developing emission factors for clay bricks and aggregate, we analyzed the GHG benefit of using recycled-content concrete. As shown in Exhibit 2, we modeled two types of recycled-content concrete: (1) concrete with 15 percent of cement replaced with fly ash and (2) concrete with 20 percent of cement replaced with fly ash.

Exhibit 2. GHG Emissions Associated with Recycled-Content Concrete

Recycled Inputs	GHG Emissions from Recycled-Content Materials (MTCE/ton)
Concrete - 15% fly ash	(0.0035)
Concrete - 20% fly ash	(0.0047)

Although the emission factors for clay bricks, aggregate, and recycled-content concrete are much smaller than for other materials, the potential for emission reductions is significant due to the high volume of these materials discarded each year. This is particularly true for recycled-content concrete, which has the potential for 3-5 MMTCE per year of emission reductions. Estimates of potential emission reductions by material type are presented in Exhibits 3 and 4. Emission reduction potentials for some key materials included in municipal solid waste are provided for comparison.

Exhibit 3. Potential GHG Emissions Associated with Various Building Materials[1]

Material	Annual Discards (tons)	Source Reduction: Emission Reduction Potential (MTCE)	Recycling: Emission Reduction Potential (MTCE)
Clay Bricks	NA	NA	NA
Concrete	200,000,000	NA	(257,000)
Aluminum	3,170,000	(8,036,000)	(13,063,000)
Steel	2,880,000	(2,267,000)	(1,409,000)
Glass	12,770,000	(1,746,000)	(973,000)
Dimensional lumber	35,100,000	(19,272,000)	(23,492,000)

Sources: Discarded concrete estimate provided by William Turley, Executive Director, Construction Materials Recycling Association; U.S. EPA, 1998 and Wilburn, D.R., and Gonnan, T.G. 1998. *Aggregates from natural and recycled sources—Economic assessments for construction applications*: U.S. Geological Survey Circular 1176. Discarded aluminum, steel, and glass estimates from U.S. EPA, 2002. *Municipal Solid Waste in the United States: 2000 Facts and Figures.* Discarded lumber estimates from MecKeever, David B. 1999. "How Woody Residuals are Recycled in the United States." *Biocycle.* December, pp. 33-44.

[1]Aluminum discards equal total aluminum discards in U.S. EPA 2002. Steel discards equal total steel in packaging only from U.S. EPA 2002. Metals in durable goods listed as "ferrous metals" include iron and are not disaggregated for steel. Glass discards equal all glass in municipal solid waste from U.S. EPA 2002. Dimensional lumber discards equal all C&D wood discards.

Exhibit 4: Potential GHG Emissions Associated with Recycled-Content Concrete[2]

Material	Annual Production (tons)	Recycled-Content Concrete: Emissions Reduction Potential (MTCE)
Concrete - 15% fly ash	970,000,000	(3,392,000)
Concrete - 20% fly ash	970,000,000	(4,541,000)

Source: Terry Collins, Portland Cement Association; USGS 2001. *2000 Minerals Yearbook: Cement.*

The emission reductions associated with recycled-content concrete are derived from the substitution of fly ash for cement, which is a GHG-intensive input to the concrete manufacturing process. In the concrete mixes analyzed, fly ash comprised only 1.43 and 1.92 percent of the mix by weight, respectively. When emissions are expressed in terms of MTCE per ton of fly ash, rather than per ton of concrete, the corresponding emission factor is 0.244 MTCE/ton (see Exhibit 5). These results are consistent with those published in a 1998 U.S. EPA study; the study estimated savings of 0.22 MTCE/ton of concrete made with fly ash in place of cement.[3]

Exhibit 5: GHG Emissions Associated with Substituting Fly Ash Use for Cement in Concrete Production

Material	Net Recycling Emission Factor (MTCE/ton fly ash)
Fly ash	(0.244)*

* Note that this value applies to fly ash that is used as a substitute for cement in concrete production.

Because the materials we analyzed for this report do not fit exactly into our existing life-cycle framework, we only developed emission factors for the waste management techniques relevant to each material. For example, none of the materials would result in combustion emissions, so combustion emission factors were not developed. The basis for these decisions is described in more detail in the July 2002 ICF Consulting memo *Feasibility of Developing Product-level Emission Factors for Materials Commonly Used in Green Building/Green Design.*

[2] According to USGS 2001, the total consumption of cement in 2000 was 120,700,000 tons. It was assumed that 100 percent of this cement was used to make concrete and that 12.5 percent of the concrete was cement by weight. Data on concrete production are difficult to obtain because so much of the concrete is mixed on site. Until better data are available, we recommend using this value as a proxy for concrete production.

[3] U.S. EPA 1998. *Greenhouse Gas Emissions from the Management of Selected Materials: Polypropylene Waste, Cement Kiln Dust, and Construction and Demolition Concrete.*

CLAY BRICK

Our effort to develop an emission factor for source reducing (i.e., re-using) clay bricks relies primarily on estimates of energy intensity and fuel use provided in the Athena Institute report titled *Life Cycle Analysis of Brick and Mortar Products*. These data are shown in Appendix A.

Our results indicate, as expected, that source reduction is preferable from a GHG standpoint to landfilling (see Exhibit 6). As shown in Exhibit 6, the clay brick emission factor for source reduction has a negative value, indicating that this practice leads to a reduction in GHG emissions.

Exhibit 6. GHG Emissions Associated with Clay Brick

Material	Net Source Reduction Emissions For 100 Percent Virgin Inputs (MTCE/ton)	Net Landfilling Emissions (MTCE/ton)	Delta in Net Emissions, SR vs. Landfilling (MTCE/ton)
Clay Brick	(0.07)	0.01	(0.08)

The single most important component of the analysis is the energy required to manufacture bricks. Other typical factors such as landfill carbon sequestration and landfill methane emissions do not apply to clay bricks. The remainder of this section describes assumptions and inputs to the calculation of emission factors for source reducing and landfilling clay bricks.

Energy-Related Emissions

In their September 1998 report, *Life Cycle Analysis of Brick and Mortar Products,* the Athena Institute analyzed process and transportation energy for manufacturing clay bricks from virgin materials. Athena's life-cycle data focuses on brick production in Canada, but rationalizes its use of both U.S. and Canadian data by asserting that "the Canadian and U.S. brick and cement/concrete industries are generally integrated." This statement indicates that Athena's data is an acceptable substitute for U.S.-specific data.

Clay bricks are not energy-intensive products, on a BTU per ton basis, as shown in Exhibit 7 below.[4] Athena reports that the primary fuel consumed in brick production is natural gas. Electricity is the second most prevalent fuel used, followed by diesel and light oil.

Exhibit 7. Raw Material Acquisition and Manufacturing (RMAM) Energy

Material	Process Energy (million BTU/ton)	Transportation Energy (million BTU/ton)	Total Energy (million BTU/ton)
Clay Brick	4.76	0.03	4.79

[4] For comparison, most other MSW materials in our database have total energy requirements in the range of 20 to 70 million BTU/ton.

Landfill Fate – Methane and Carbon Sequestration

When clay brick is disposed, it remains undecomposed in the landfill due to the composition of the material. According to the Athena Institute, clay brick is composed of: (1) common clay—a fine-grained mineral composed of an alumino silicate structure with additional iron, alkalis and alkaline earth elements; and (2) shale—a sedimentary rock composed chiefly of clay minerals. We assume that clay brick does not generate methane in landfills.

We conducted an Internet search to find information on carbon storage in clay bricks, but could not find any research indicating that clay bricks act as carbon sinks. However, we did find a few reports lauding the carbon storage benefits of wood building products as opposed to brick and concrete building materials. These studies indicated that brick products do not store carbon, supporting our assumption that carbon sequestration in landfills would be negligible.

Current Mix

To estimate GHG emissions associated with MSW management options, we analyzed whether the baseline scenario should include a mix of both virgin and recycled inputs. Athena discusses the use of sewage sludge, contaminated soils, and fly ash when making clay bricks, but does not provide values that could be useful for calculating a current mix estimate. It describes these practices as feasible, but not often practiced at this time. Athena also notes that 4-8 percent of the volume of raw materials used in brick production is comprised of damaged, finished ware that has been recycled back into raw materials. Because these inputs reflect pre-consumer recycling, not post-consumer recycling, the energy associated with manufacturing brick with these inputs would still be considered "virgin" in our nomenclature. Based on the information provided by Athena, it appears that there is very little (if any) recycled-content brick being produced. Therefore, we assumed that virgin production is the same as production using the current mix (nearly 100 percent virgin inputs).

Calculation of Emission Factors

To calculate the emission factors for source reduction for clay brick, we summed raw material acquisition and manufacturing GHG emissions for current mix of inputs and zero waste management emissions.

As described above, landfilling clay bricks is not expected to result in measurable methane emissions or carbon storage. Therefore, the landfill emission factor for clay bricks includes only the emissions associated with transporting the material to the landfill. We used a default value (0.01 MTCE/ton) for these emissions, based on data obtained from Franklin Associates, Ltd., *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.) September 1994, p. I-5. We use this default value for all of the MSW materials analyzed in *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (2^{nd} Edition).

CONCRETE (RECYCLED AND USED IN PLACE OF VIRGIN AGGREGATES)

In developing an emission factor for using crushed concrete as a substitute for virgin aggregates, we relied primarily on data provided in the following two sources:

- the U.S. Geological Survey (USGS) Circular 1176, *Aggregates from Natural and Recycled Sources;* and
- the Athena Institute report titled *Cement and Structural Concrete Products.*

These data are shown in Appendix B.

According to our results, recycling concrete is preferable to landfilling from a GHG standpoint. As shown in Exhibit 8, the aggregate emission factor for recycling has a (slightly) negative value, indicating that the use of recycled aggregates results in a reduction of GHG emissions. This analysis assumes that for "virgin" concrete, aggregate is transported by truck for 30 miles (with corresponding energy CO_2 emissions), and that recycled concrete is crushed and reused on-site (a common practice), resulting in no transportation emissions.

Exhibit 8. GHG Emissions Associated with Concrete

Material	Net Recycling Emissions For Current Mix of Inputs (MTCE/ton)	Net Landfilling Emissions (MTCE/ton)	Delta in Net Emissions, Recycling vs Landfilling (MTCE/ton)
Concrete	(0.0013)	0.01	(0.012)

Because the results are driven largely by assumptions on transportation distances for virgin and recycled aggregate, we have also expressed the net emission factor for recycling as a function of distance:

Net Recycling Emissions (MTCE/ton) = $-3.58E\text{-}5 * d_1 + 4.05E\text{-}5 * d_2 - 2.14E\text{-}4$

Where: d_1 is the distance, in miles, for transporting virgin aggregate, and
d_2 is the distance, in miles, for transporting the recycled aggregate (crushed concrete)

The key components of the analysis are the energy required to mine, process, and transport aggregate. Also, as is clear from Exhibit 8, the benefits of recycled concrete (as crushed aggregate) are largely the avoided landfilling emissions (which are an order of magnitude higher than net recycling emissions). Thus, the overall result is very sensitive to the accuracy of the landfill emission factor, and since we are expressing recycling as a function of distance, for this comparison it may also be worthwhile in the future to provide a landfill emission estimate as a function of transportation distance. Below is a discussion of the assumptions and inputs to the calculation of emission factors for recycling concrete for reuse as aggregates.

Energy-Related Emissions

We relied on two primary sources of information for energy-related emissions.

- The June 1998 USGS report, *Aggregates from Natural and Recycled Sources,* provides an economic assessment of increased use of recycled aggregates in the construction industry. The report presents information on the process and transportation energy for recycled aggregates and the transportation energy for virgin aggregates.

- Aggregates are the largest component of concrete by weight, and an analysis of the process energy for manufacturing virgin aggregate appeared in the Athena Institute's September 1993 report, *Cement and Structural Concrete Products*. While Athena's data focused on aggregate production in Canada, industry experts have confirmed that aggregate production in the U.S. and Canada is performed with similar equipment and techniques. Thus, Athena's process energy data is an acceptable substitute for U.S.-specific data. An update of this report was published in October 1999, but none of the aggregate process energy had changed.

Aggregates are not energy-intensive products, on a BTU per ton basis, as shown in Exhibit 9 below. Athena reports that the two fuels consumed in aggregate production are diesel (for the mining process and transportation) and electricity (for the crushing process). No other fuels are utilized. Transportation energy accounts for more than half of the total energy in virgin aggregate.

The total energy required to produce virgin aggregate is higher than that required to produce recycled aggregate (see Exhibit 9). The higher total energy value is driven by energy requirements for mining and transportation, both of which are zero for recycled aggregates. Transportation distances are assumed to be zero for recycled aggregates, resulting in zero transportation energy. In highway improvement and other projects, old concrete is frequently crushed and reused on-site using portable equipment. As noted earlier, we assume a distance of 30 miles for virgin aggregates.

Exhibit 9. Raw Material Acquisition and Manufacturing (RMAM) Energy

Material	Process Energy (million BTU/ton)		Transportation Energy (million BTU/ton)		Total Energy (million BTU/ton)	
	Virgin	Recycled	Virgin	Recycled	Virgin	Recycled
Aggregates	0.040	0.032	0.054	0	0.094	0.032

Landfill Fate – Methane and Carbon Sequestration

Due to its inert components, concrete does not decompose when deposited in landfills. Concrete is composed of Portland cement, water, air, and coarse and fine aggregates (crushed stone and sand). In the production of cement, limestone is baked at high temperatures to convert calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and carbon dioxide (CO_2). The CO_2 is released into the atmosphere, leaving no carbon in the cement. The aggregates are inert minerals—primarily silica and limestone—and do not decompose. We assume that concrete does not generate methane in landfills.

Although concrete can absorb some atmospheric CO_2 in the curing process, we did not find any research to quantify carbon storage associated with landfilled concrete. A 1996 study by the Forest & Wood Products Research & Development Corporation indicates that concrete does not store carbon, supporting our assumption that carbon sequestration in landfills would be negligible. The results of this study are presented in Exhibit 10.

Exhibit 10. Carbon Released and Stored in the Manufacture of Building Materials[5]

Material	Carbon	Carbon Released	Carbon Stored
Rough sawn timber	30	15	250
Steel	700	5320	0
Concrete	50	120	0
Aluminum	8700	22000	0

Calculation of Emission Factors

The recycling emission factor incorporates the difference between manufacture from virgin and recycled inputs for energy-related GHG emissions (manufacturing process and transportation). We assume that 100 percent of the materials recovered were retained (i.e., that there were no losses between when the concrete was recovered and when the recycled aggregates were utilized). Because process energy data for virgin aggregates is split between fine and coarse aggregates, we created a single set of energy data for virgin aggregates by apportioning the energy requirements of fine and coarse aggregate production by their respective shares of total U.S. aggregate production, as reported in the USGS *Minerals Yearbook*. Recycled aggregate is not subdivided into fine and course. For the recycling process, we assumed that all recycling and reuse occurs on-site, resulting in zero transportation energy. Since this is not always the case, we also calculated energy and emissions as a function of distance traveled, as discussed above.

The landfill emission factor for concrete includes only the emissions associated with transporting the material to the landfill. We used a default value (0.01 MTCE/ton) for these emissions, based on data obtained from Franklin Associates, Ltd., *The Role of Recycling in Integrated Solid Waste Management to the Year 2000*. We use this default value for all of the MSW materials analyzed in *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (2nd Edition).

[5] Source: Presented in Ferguson, I., La Fontaine, B., Vinden, P., Bren, L., Hateley, R. and Hermesec, B. 1996. 'Environmental Properties of Timber," Research Paper commissioned by the Forest & Wood Products Research & Development Corporation.

RECYCLED-CONTENT CONCRETE

As defined in this memo, recycled-content concrete is concrete in which fly ash has been used as a partial substitute for cement. Of course, as described above, crushed concrete could also substitute for aggregate in concrete production, but that is not part of the scenario evaluated here. In developing emission factors for recycled-content concrete, we relied primarily on data from two sources, including:

- Estimates of process and transportation energy in the production of concrete from the Portland Cement Association's (PCA) 2000 study, *Environmental Life Cycle Inventory of Portland Cement Concrete;* and
- Some process energy data and non-energy process emissions data from the Athena Institute report, *Cement and Structural Concrete Products*.

These data are shown in Appendix C. We also reviewed the *Sector-Specific Issues and Reporting Methodologies Supporting the General Guidelines for the Voluntary Reporting of Greenhouse Gases under Section 1605(b) of the Energy Policy Act of 1992*;[6] this reference has been used by several voluntary reporters to calculate GHG emission reductions associated with using fly ash. Because the guidance is site-specific (based on the specific fuel used by the cement plant), we did not use it here. The results of applying the 1605b guidance are broadly consistent with the estimates we developed, however.

We developed two emission factors for concrete—one in which fly ash offsets 15 percent of the cement used and one in which fly ash offsets 20 percent of the cement used. Given that cement comprises about 10 percent of concrete, by weight, these formulations are equivalent to total fly ash concentrations of roughly 1.5 percent and 2.0 percent. As shown in Exhibit 11, there are GHG benefits of using concrete with fly ash substituting for cement. These benefits are small on a per ton basis, but given the large volume of concrete used nationally, the cumulative effect may be significant.

Exhibit 11. GHG Emissions Associated with Recycled-Content Concrete

Material	Total Emissions (MTCE/ton)	Net Emissions for Recycled Content, compared to 0% fly ash (MTCE/ton concrete)
Concrete (cement=0% fly ash)	0.0257	
Concrete (cement=15% fly ash)	0.0222	-0.0035
Concrete (cement=20% fly ash)	0.0210	-0.0047

The composition of concrete mixes vary widely, depending on local conditions, economics, and project specifications. In some situations, it is possible or even desirable to replace up to 50 percent of cement with fly ash. Using the data gathered during this study, we developed an equation to express emissions as a function of the fly ash content.

Emission factor (MTCE/ton concrete) = -0.0246 * Fly ash content + 0.0002

Where: Fly ash content = The percentage of cement in the mix that is replaced with fly ash.

Using this equation, the emission factors for mixes that replace 25 percent and 50 percent of

[6] http://www.eia.doe.gov/oiaf/guidelns.htm#vol1

cement with fly ash are –0.0060 MTCE/ton concrete and –0.0121 MTCE/ton concrete, respectively.

Because fly ash is responsible for the GHG emissions savings in spite of being such a small component of concrete, it is useful to look at these emissions expressed in terms of MTCE per ton of fly ash, rather than per ton of concrete. These results are presented in Exhibit 12.

Exhibit 12: GHG Emissions Associated with Substituting Fly Ash for Cement in Concrete Production

Material	Recycled-Content Concrete: Emission Factor (MTCE/ton fly ash)
Fly ash	(0.244)

The results of this analysis are driven by the energy and non-energy process emissions associated with cement production, an essential component of concrete. There are no emissions associated with production of fly ash – it is a byproduct of coal combustion for energy, and would otherwise be landfilled as waste – and thus, to the extent that fly ash can substitute for cement, it reduces GHG emissions. Below is a discussion of the assumptions and inputs to the calculation of emission factors for recycled-content concrete.

Energy-Related Emissions

The majority of energy consumed in concrete production is associated with cement production, even though cement only accounts for approximately 10 percent of concrete, by weight. The other components are primarily aggregates, a low-energy product, so the overall energy intensity of concrete is relatively low.

Fly ash with a low carbon content (less than 3-4 percent) is used in concrete without any additional processing. In the past, most U.S. fly ash fell into this category. However, at power plants that have instituted new NO_x emissions controls, the carbon content is too high to be used without further processing (5-9 percent). We did not include energy associated with fly ash processing in this analysis because this process is not currently occurring on a large scale.[7]

Because there are a wide variety of concrete mixes and products in use today, the PCA report selected six different mixes and several different concrete products to study. Here we have chosen to analyze three versions of 3,000 p.s.i. ready-mix concrete, the most common specification for typical applications. The three versions have varying amounts of fly ash replacing the cement in the mixture: zero, 15, and 20 percent (equivalent to total fly ash concentrations of zero, 1.5 percent, and 2.0 percent). The proportions of coarse and fine aggregate are the same in all three mixes.

The process and transportation energy requirements for concrete are shown below in Exhibit 13. The process energy is based on the weighted average across all the components (cement, fly ash, aggregates).

The process energy for cement is based on the value reported by PCA, 0.45 million BTU per ton of concrete (no fly ash content). We also used the fuel mix reported by PCA. PCA reports that coal is the

[7]Based on screening level calculations, processing the fly ash would add 0.012 and 0.016 million BTU/ton concrete to the 15% fly ash and 20% fly ash mixtures, respectively.

primary fuel consumed in concrete production, followed by diesel, electricity, petroleum coke, natural gas, and waste.

For data on the process energy required for aggregate production, we relied on the Athena Institute's September 1993 report, *Cement and Structural Concrete Products*. This study provided point estimates, which were within the range of values reported by PCA.

Our transportation energy estimates are based on assuming truck transport for distances of 60 miles for both cement and fly ash, and 30 miles for aggregates. For the two concrete mixes with fly ash content, the energy associated with landfilling the ash would be avoided. We factored this into our calculations, as shown in Exhibit 13.

Exhibit 13. Raw Material Acquisition and Manufacturing (RMAM) Energy

Material	Process Energy, million BTU/ton	Transportation Energy, million BTU/ton	Avoided Energy for Landfilling, million BTU/ton	Total Energy, million BTU/ton
Concrete (Cement = 0% Fly Ash)	0.57	0.05	-	0.62
Concrete (Cement = 15% Fly Ash)	0.50	0.05	(0.004)	0.55
Concrete (Cement = 20% Fly Ash)	0.48	0.05	(0.006)	0.52

Process-Related Non-Energy Emissions

As discussed above, cement is produced by baking limestone at high temperatures to convert calcium carbonate ($CaCO_3$) to calcium oxide (CaO) and carbon dioxide (CO_2). The CO_2 is emitted into the atmosphere. Although cement only represents roughly 10 percent of concrete by weight, this non-energy process emission is a significant portion of the total emissions associated with concrete manufacture. Non-energy process emissions data for cement production was taken from the Athena Institute report and is presented in Exhibit 14.

Landfill Fate – Methane and Carbon Sequestration

Fly ash does not decompose when deposited in landfills. It is a byproduct of coal-fired utility plants. During combustion, the majority of the carbon in coal is emitted as CO_2. The remainder is more than 97 percent mineral content and does not decompose; therefore, it is not expected to generate methane in landfills.

Calculation of Emission Factors

The emission factors we developed compare the zero percent fly ash mix, or "virgin" mix, with the 15 percent fly ash mix and the 20 percent fly ash mix. In each case, the emissions associated with the recycled-content products are subtracted from the emissions associated with 100 percent virgin inputs. A summary of the calculation of the emission factors that appeared earlier in Exhibit 15 is shown below.

Exhibit 14. Non-Energy Industrial Process Emissions

Material	$MTCO_2$/Ton Product	MTCE/Ton Product
Concrete (Cement = 0% Fly Ash)	0.043	0.012
Concrete (Cement = 15% Fly Ash)	0.037	0.010
Concrete (Cement = 20% Fly Ash)	0.035	0.009

Exhibit 15: Calculation of Emission Factors

Material	Process Energy Emissions, MTCE/ton	Transportation Emissions, MTCE/ton	Avoided Energy for Landfilling Emissions, MTCE/ton	Non-Energy Process Emissions, MTCE/ton	Total Emissions, MTCE/ton	Net Emissions for Recycled Content, compared to 0% fly ash, MTCE/ton concrete
Concrete (Cement = 0% Fly Ash)	0.0130	0.0009	–	0.0118	0.0257	--
Concrete (Cement = 15% Fly Ash)	0.0114	0.0009	(0.0001)	0.0101	0.0222	(0.0035)
Concrete (Cement = 20% Fly Ash)	0.0108	0.0009	(0.0002)	0.0095	0.0210	(0.0047)

Appendix A. Data Used to Derive Emission Factor for Brick and Mortar (million Btu/ton)[1]

Exhibit A-1: Process energy data for the production of a short ton of brick and mortar	
Fuel	**Combustion Process Energy per Ton (million Btu)**
Natural gas	2.672
Light oil	0
Diesel road	0.081
Electricity	2.009
Total	**4.762**

Exhibit A-2: Transportation energy data for the production of a short ton of brick and mortar	
Fuel	**Transportation Energy per Ton (million Btu)**
Diesel road	0.026
Total	**0.026**

[1] Athena Sustainable Materials Institute. 1998. *Life Cycle Analysis of Brick and Mortar Products.* Ottawa, Canada.

Appendix B. Data Used to Derive Recycled Aggregate Emission Factor

Exhibit B-1: Process energy data for the production of a short ton of aggregate, weighted by national proportion of coarse and fine aggregate

		(a)	(b)	(c)
Type of Aggregate	**Fuel**	**Combustion Process Energy per Ton of Each Type (million Btu)[1]**	**Percentage of Total U.S. Aggregate Production in 2001 by Aggregate Type[2]**	**Total Process Energy per Ton, Weighted by Type (million Btu) (=a x b)**
Coarse Aggregate	Electricity	0.009	59%	0.006
	Diesel	0.023		0.014
Fine Aggregate	Electricity	0.028	41%	0.011
	Diesel	0.023		0.009
	Total			**0.040**

Exhibit B-2: Transportation energy data for the production of a short ton of aggregate, weighted by national proportion of coarse and fine aggregate

		(a)	(b)	(c)
Type of Aggregate	**Fuel**	**Combustion Transportation Energy per Ton of Each Type (million Btu)[3]**	**Percentage of Total U.S. Aggregate Production in 2001 by Aggregate Type[2]**	**Total Transportation Energy per Ton, Weighted by Type (million Btu) (=a x b)**
Coarse	Diesel	0.061	59%	0.018
Fine Aggregate	Diesel	0.043	41%	0.036
	Total			**0.054**

Exhibit B-3: Process energy data for the production of a short ton of recycled aggregate[4]

Type of Aggregate	**Fuel**	**Combustion Process Energy per Ton (million Btu)[3]**
Recycled Aggregate	Electricity	0.032
Total		**0.032**

[1]Athena Sustainable Materials Institute. 1993. *Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates: Cement and Structural Concrete Products.* Ottawa, Canada.

[2]USGS. 2002. *Mineral Industry Surveys: Crushed Stone and Sand and Gravel in the Second Quarter 2002.* United States Geological Survey, Reston, VA. September.

[3]Wilburn, David R. and Goonan, Thomas G. 1998. *Aggregates from Natural and Recycled Sources: Economic Assessments for Construction Applications--A Materials Flow Analysis.* U.S. Geological Survey Circular 1176, U.S. Geological Survey, Reston, VA.

[4]It was assumed that recycled aggregate requires zero transportation energy.

Appendix C. Data Used to Derive Emission Factor for Recycled-Content Concrete

Exhibit C-1: Process energy data for the production of a cubic yard of recycled-content concrete (million btu/cubic yard)[1]

		(a)	(b)	(c)	(d)	(e)
Production Process	**Fuel**	**0% Fly Ash Cement**	**15% Fly Ash Cement**	**20% Fly Ash Cement**	**25% Fly Ash Cement[3]**	**50% Fly Ash Cement[3]**
Cement Production[2]	Coal	0.511	0.435	0.409	0.383	0.256
	Gasoline	0	0	0	0	0
	LPG	0	0	0	0	0
	Middle	0.007	0.006	0.006	0.005	0.004
	Natural	0.064	0.054	0.051	0.048	0.032
	Pet. Coke	0.127	0.108	0.102	0.095	0.064
	Residual	0.001	0.001	0.001	0.001	0.001
	Waste	0.071	0.060	0.056	0.053	0.036
	Electricity	0.090	0.077	0.072	0.068	0.045
	Subtotal	0.871	0.741	0.697	0.653	0.436
Aggregate Production[2]						
Fine	Diesel fuel	0.022	0.022	0.022	0.022	0.022
	Electricity	0.009	0.009	0.009	0.009	0.009
Course	Diesel fuel					
	Electricity	0.016	0.016	0.016	0.016	0.016
	Subtotal	0.020	0.020	0.020	0.020	0.020
Plant	Diesel	0.139	0.139	0.139	0.139	0.139
	Natural	0.030	0.030	0.030	0.030	0.030
	Electricity	0.010	0.010	0.010	0.010	0.010
	Subtotal	0.179	0.179	0.179	0.179	0.179
	Total	**1.117**	**0.987**	**0.943**	**0.899**	**0.681**

[1] One cubic yard of concrete is assumed to weigh 3,913 pounds, or 1.957 tons (PCA 2000). Million btu/cubic yard were then converted to million btu/ton by multiplying by 0.511 cubic yards/ton.

[2] PCA. 2000. *Environmental Life Cycle Inventory of Portland Cement Concrete*. Portland Cement Association. Serial No. 2137.

[3] Calculated using energy values from column A (percent *not* fly ash x energy for zero-percent fly-ash).

Exhibit C-2: Transportation energy data for the production of a cubic yard of recycled-content concrete[1] (million btu/cubic yard)						
		(a)	(b)	(c)	(d)	(e)
Fuel	**Concrete Input**	**0% Fly Ash**	**15% Fly Ash**	**20% Fly Ash**	**25% Fly Ash[2]**	**50% Fly Ash[2]**
Diesel	Cement	0.017	0.014	0.013	0.013	0.009
	Coarse	0.042	0.042	0.042	0.042	0.042
	Fine	0.031	0.031	0.031	0.031	0.031
	Fly ash	0	0.002	0.003	0.004	0.009
	Total	**0.089**	**0.089**	**0.089**	**0.089**	**0.089**

[1] Athena Sustainable Materials Institute. 1993. *Raw Material Balances, Energy Profiles and Environmental Unit Factor Estimates: Cement and Structural Concrete Products*. Ottawa, Canada. One cubic yard of concrete is assumed to weigh 3,913 pounds, or 1.957 tons (PCA 2000). Million btu/cubic yard were then converted to million btu/ton by multiplying by 0.511 cubic yards/ton.

[2] Calculated using energy values from column A (percent *not* fly ash x energy for zero-percent fly-ash).